Texas A&M Transportation Institute
The Texas A&M University System
3135 TAMU
College Station, TX 77843-3135
979-845-8829
Fax: 979-845-6008
http://tti.tamu.edu
shawn-turner@tamu.edu

June 11, 2014

TECHNICAL MEMORANDUM

TO: Wang Zhang, Maricopa Association of Governments (MAG)

FROM: Shawn Turner, Texas A&M Transportation Institute (TTI)

SUBJECT: Task 1 – Identifying and Measuring Freeway (and Arterial) Bottlenecks Using Private-Sector Speed Data

This memo documents the findings and conclusions of Task 1, Data Collection for Task Order A-02-543-G. The goal of Task 1 was to identify and evaluate, using a variety of congestion measures, a list of existing bottlenecks in the MAG region for further evaluation. These results are included in this memo.

1. Introduction

Ongoing improvements in traffic data collection are increasing the ability to accurately identify and quantify traffic congestion problems. Commercially-available travel speed data, with its comprehensive temporal-spatial coverage and excellent data quality, enable transportation analysts to look at traffic bottleneck problems thoroughly from a new angle. The Maricopa Association of Governments (MAG) (the designated metropolitan planning organization of Phoenix, Arizona) and the Texas A&M Transportation Institute (TTI) are conducting a bottleneck study in the Phoenix metropolitan area through collaboration.

The study first applies an innovative bottleneck identification algorithm developed by TTI. This algorithm is specially tailored for archived private-sector speed data, which do not provide real-time speeds but rather average speeds over multiple days. After bottlenecks are identified, numerous congestion measures are calculated, and data visualizations are prepared for these bottlenecks. Heavily using private-sector speed data and other datasets, the study confirms, measures, ranks, and prioritizes all identified bottlenecks according to vehicle delay, traveler delay, truck delay, or reliability. As a case study, the prioritized bottlenecks are examined for in-depth investigation and evaluation. A concurrent traveler information database is studied along with the speed database to categorize the congestion type. Additional data on freeways, ramps, and local streets/intersections, including vehicle trajectory and origin-destination (OD) data, in a concentrated bottleneck area are collected to help understand the causes of bottlenecks. This study constructs a micro-simulation model of the prioritized bottlenecks to facilitate operation and planning efforts.

2. Bottleneck Identification Algorithm

This algorithm applies an auto-segmentation methodology[1] to determine regions of higher traffic congestion for purposes of identifying potential bottleneck locations. The algorithm exploits certain features found in 15-minute average weekday speed data, which yield a large amount of information about recurring congestion. The algorithm begins by comparing average annual weekday 15-minute speeds among adjacent Traffic Message Channel (TMC) links to determine the degree of similarity or dissimilarity between the respective speed distributions, and therefore whether traffic conditions are similar enough to group these adjacent links. Straightforward and relatively simple calculations provide a single-number criterion indicating the relative degree of congestion similarity between pairs of adjacent roadway links. The bottleneck identification process then focuses on groupings of more highly congested links as potential bottleneck candidates.

The bottleneck identification algorithm only relies on aggregated speed information provided by third-party data providers; as a result, the algorithm obtains broad coverage of freeway networks. It is not dependent on high-quality continuous real-time traffic information. The algorithm uses all available average speed data to create a distribution of average speeds irrespective of time (i.e., it is not just based on a peak period). The use of all data provides more discriminating power to the algorithm to match similar links. This confers an additional advantage in that the algorithm is relatively robust in the presence of missing data, as long as the missing speeds do not overwhelmingly occur at times corresponding to congested traffic (i.e., peak periods).

For this study, the bottleneck identification algorithm used NAVTEQ 2012 average annual 15-minute directional speeds by day of the week. Figure 1 shows these speeds for two adjacent TMC links (hereafter referred to as simply *links*), Link 1 and Link 2. The names of the links denote the order in which they are traversed for the given direction of traffic. In this example, Link 1 appears more congested than Link 2—average speeds during the afternoon peak period plunge below 30 mph.

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[1] Wikander, J., W. Eisele, and D. Schrank, *Auto-Segmentation Method for MAP-21 Performance Measure Reporting Using Large Statewide Speed Datasets,* To be Published in Forthcoming *Transportation Research Record*, Washington, D.C. January 2015 (Estimated).

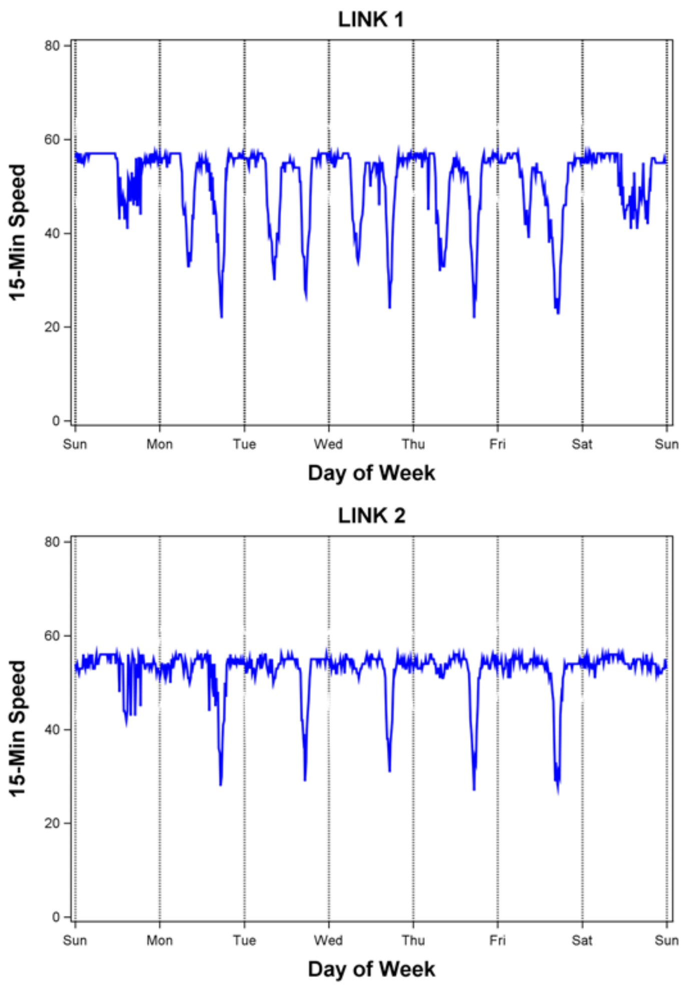

Figure 1: Link speed profile from two adjacent links

Speed distributions for each link are then constructed by ordering speeds from smallest to largest, disregarding time of day. Comparisons of speed distributions for pairs of adjacent links are the building blocks of the bottleneck identification algorithm. If the congestion conditions are the same in both links, then the distributions of speeds should be essentially the same (i.e., adjacent links with similar congestion should have roughly the same proportion of slow speeds). If instead one link is more congested than the other, then the distribution of speeds in the congested link should have a larger proportion of slower speeds than that of the less congested link.

Linear regression of one distribution on the other produces a measure of relative congestion between the links, shown in Figure 2. This measure is used to judge whether adjacent roadway links exhibit similar traffic patterns.

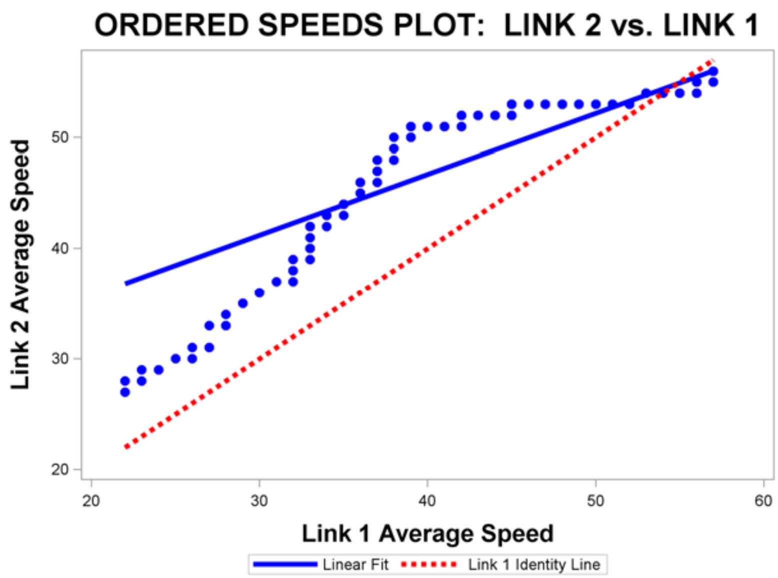

Figure 2: Ordered speeds on two adjacent links

If the distributions of the two sets of ordered speeds are the same, then the slope of the fitted line should correspond to unity. The difference between the slopes of the fitted and unity lines forms the basis of a relative congestion measure, illustrated in Figure 3. This measure generally describes how difficult it is to maintain free-flow speed. In practice, the regression of ordered speeds produces a fitted line, which appears "anchored" on the right end, corresponding to higher free-flow speeds at the posted speed limit; the left end, representing slower speeds, is free to "pivot" about the unity line. In this sense, the algorithm acts like a weathervane, where the gradient in relative congestion between the links determines both how far and in which direction the fitted line pivots away from the unity line.

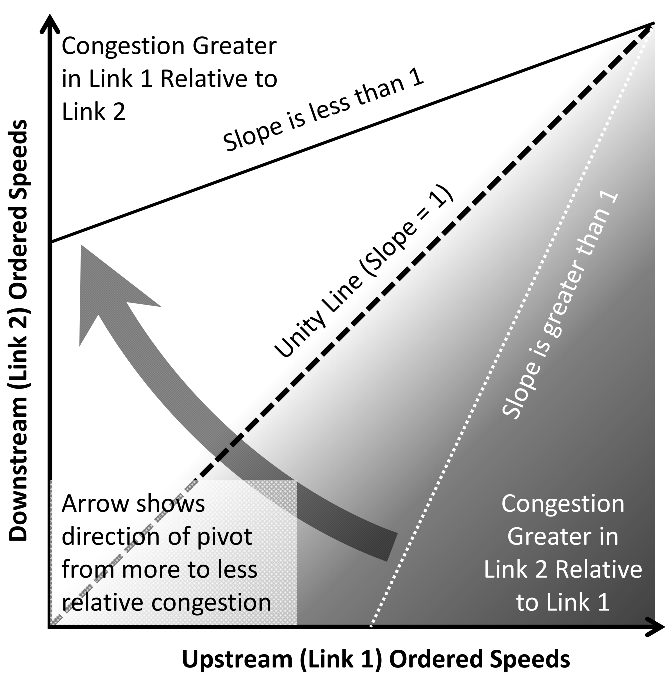

Figure 3: What does speed slope tell us?

Consider a cyclist as a real-world analogy to the operation of the relative congestion measure. In this analogy, the cyclist is trying to maintain a constant speed as he moves through a landscape with hills, valleys, basins, and plateaus. The amount of work the cyclist needs to do changes with the slope of the land, as shown in Figure 4. A cyclist climbing a steep hill will have to expend more effort to maintain his speed than if he were traveling on level ground. Conversely, a cyclist going downhill will expend less effort to maintain his speed than he would over level ground; he might even be able to coast if the downhill grade is steep enough. One can then use the slope of the land to measure proportionally how much more effort the cyclist will expend relative to traveling on level ground, with positive slopes indicating more effort, negative slopes indicating less effort, and zero slopes indicating the same effort. Here, the slope is the rate of change in altitude. Similarly, changing congestion levels on a roadway make it harder (less likely) or easier (more likely) for vehicles to travel at free-flow speeds.

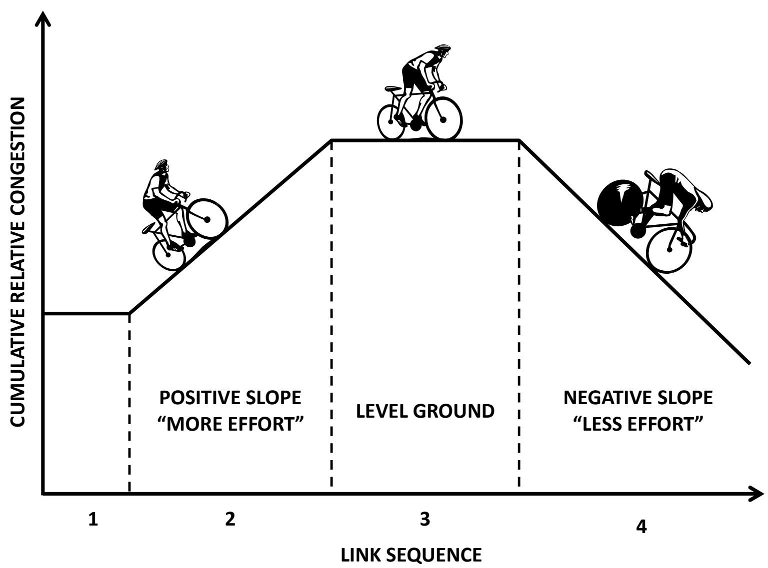

Figure 4: Relative congestion measure illustrated by cyclist

The usefulness of the relative congestion measure can be enhanced by applying it along the length of a roadway. Since the relative congestion measure is a slope, it can also be interpreted as a rate of change; specifically, it can be interpreted as the rate of change in congestion between adjacent roadway links. If one evaluates the relative congestion between all pairs of adjacent links along a roadway in the sequence corresponding to a given direction of travel, one thereby obtains a sequence of the rate of change in relative congestion for that direction. In this way, the relative congestion measure describes changes in the congestion terrain along a corridor:

- Positive values indicate congestion is going up;
- Negative values indicate congestion is going down; and
- Zero values indicate no change, or "level ground."

Furthermore, these successive rates of change can be added together cumulatively to create a cumulative congestion profile, in much the same way that changes in altitude can be cumulatively added together over distance to create a terrain plot. The following general steps summarize the auto-segmentation procedure:

1) Determine the starting point links for each section of road in the analysis.
2) Determine the sequence of links in each road section for each travel direction.
3) Obtain the changes in relative congestion between successive pairs of links in the direction of travel.
4) Compile the cumulative sum of the differences in relative congestion to obtain the cumulative congestion profiles for each direction in each road section.
5) Identify congested road segments by comparing trends in relative congestion to pre-established thresholds.

The determination of bottleneck regions follows a “catch and release” principle, where differences in relative congestion must first exceed some positive threshold over a specified number of links to “catch” the tail of a bottleneck, followed by a downstream series of decreases in relative congestion to indicate “release” at the head of the bottleneck. Generally, if the successive changes in relative congestion are consistently positive, this indicates the tail end of a potential bottleneck; conversely, if successive changes in relative congestion are consistently negative, this indicates the person has passed downstream from the head of a potential bottleneck. Continuing the cyclist analogy, a hill (bottleneck tail) is first encountered when successive slopes indicate a steepening grade. The cyclist does not consider himself to have passed the crest of the hill (bottleneck head) until he encounters a consistent downslope. In the absence of this consistent downslope, the cyclist will consider himself to either still be climbing the hill or riding along a plateau (bottleneck region). The cyclist will consider himself to be in a valley (non-bottleneck region) if he largely encounters level ground and downslope conditions.

3. Identifying Bottlenecks in the MAG Region

In order to apply the bottleneck identification algorithm to the MAG network and data, a series of network coding procedures needs to take place:

1) Confirm that the network is segmented to the exact level that the speed data are based on. For example, a network segmented by TMC is ideal for this algorithm, which analyzes average TMC-based speed.
2) Create directional routes. A route is defined as a series of connected links (TMCs) going from one end to the other end. A route should be single direction. A route should not turn at an intersection but maintain a straight direction. A route should not consist of duplicated or overlapped TMCs. TMCs on one route should be continuous without any gap.
3) Assign sequence identification (ID) to TMCs on a route. Sequence ID is generally assigned to TMCs from one end to another, from upstream to downstream. The assignment is performed per route.

In the case of MAG, directional route types mainly include northbound, southbound, eastbound, and westbound—and inner and outer for loops. All TMCs are checked so that they only belong to one specific route with a sole sequence ID.

The bottleneck identification algorithm initially identified 39 bottlenecks on freeways in the region using 2012 NAVTEQ (now known as HERE) archived speed data. The length of bottlenecks varies from a couple of miles to 30 miles.

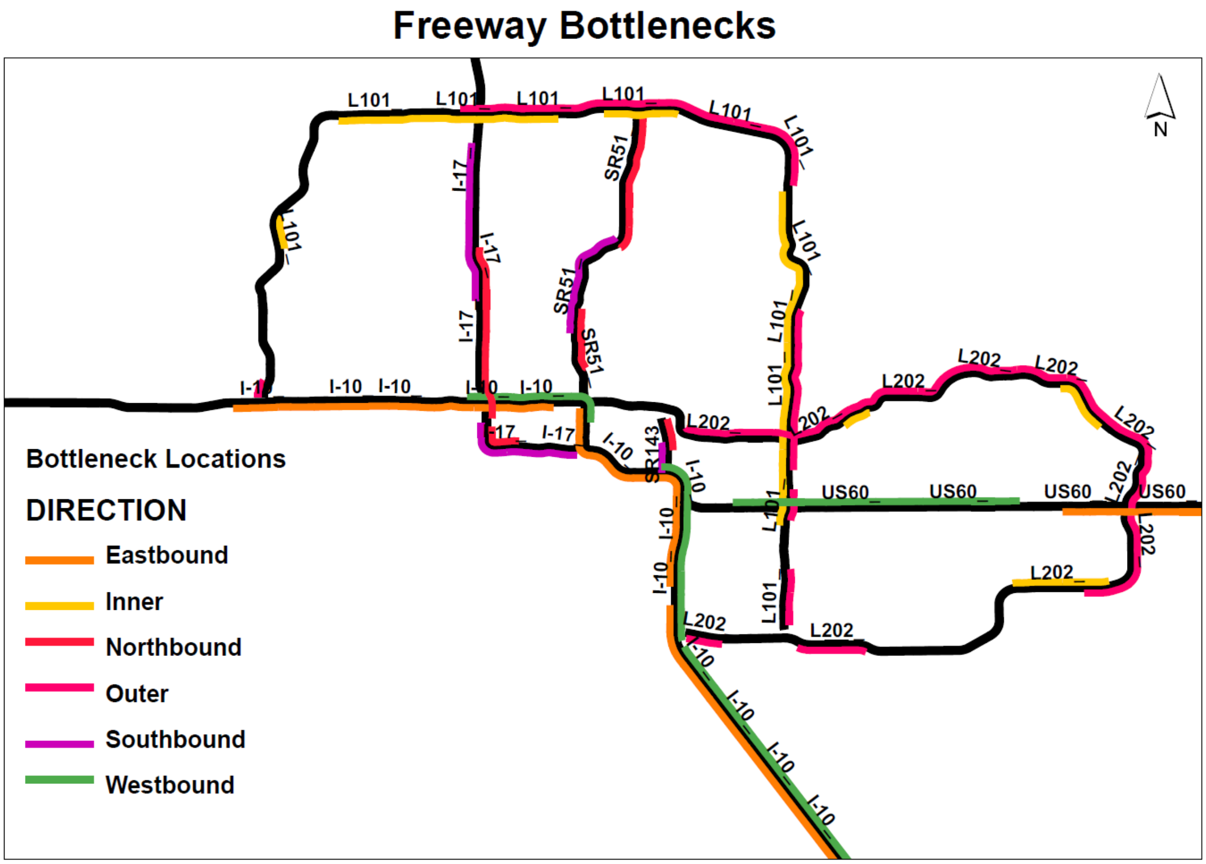

Figure 5: Initial bottleneck candidates identified by the algorithm

As an automated outcome directly from the algorithm, this part of the process can be treated as the "science" part of this analysis. To elaborate, this "science" part of the analysis is that based on discrete, quantitative data and evidence. In many analyses with limited information, "art" is often combined with science, to indicate that qualitative insight and intuition are used in combination with quantitative evidence.

While most of the freeway congestion problems in the Phoenix metropolitan region are highlighted, several issues appear:

- Some identified bottlenecks are too long, so there could be multiple isolated bottlenecks within them.
- Some bottlenecks do not necessarily show any delay in the travel per speed data.
- Some freeway segments that should have been identified as a bottleneck are missed by the algorithm.

In order to precisely identify and define all freeway bottlenecks, human judgment from people with local experience has to play a role. To further refine these bottlenecks, the following work is performed:

1) Produce a two-dimensional speed contour plot (heat map) for every bottleneck corridor, with X as the time of day and Y as the milepost from day to day. This contour plot is used to examine the congestion situation at each identified bottleneck corridor over days of the week. One plot is generated per one month of data so every bottleneck corridor has 12 plots generated. Figure 6 provides an example (I-10 westbound [WB] in downtown Phoenix in January 2012).

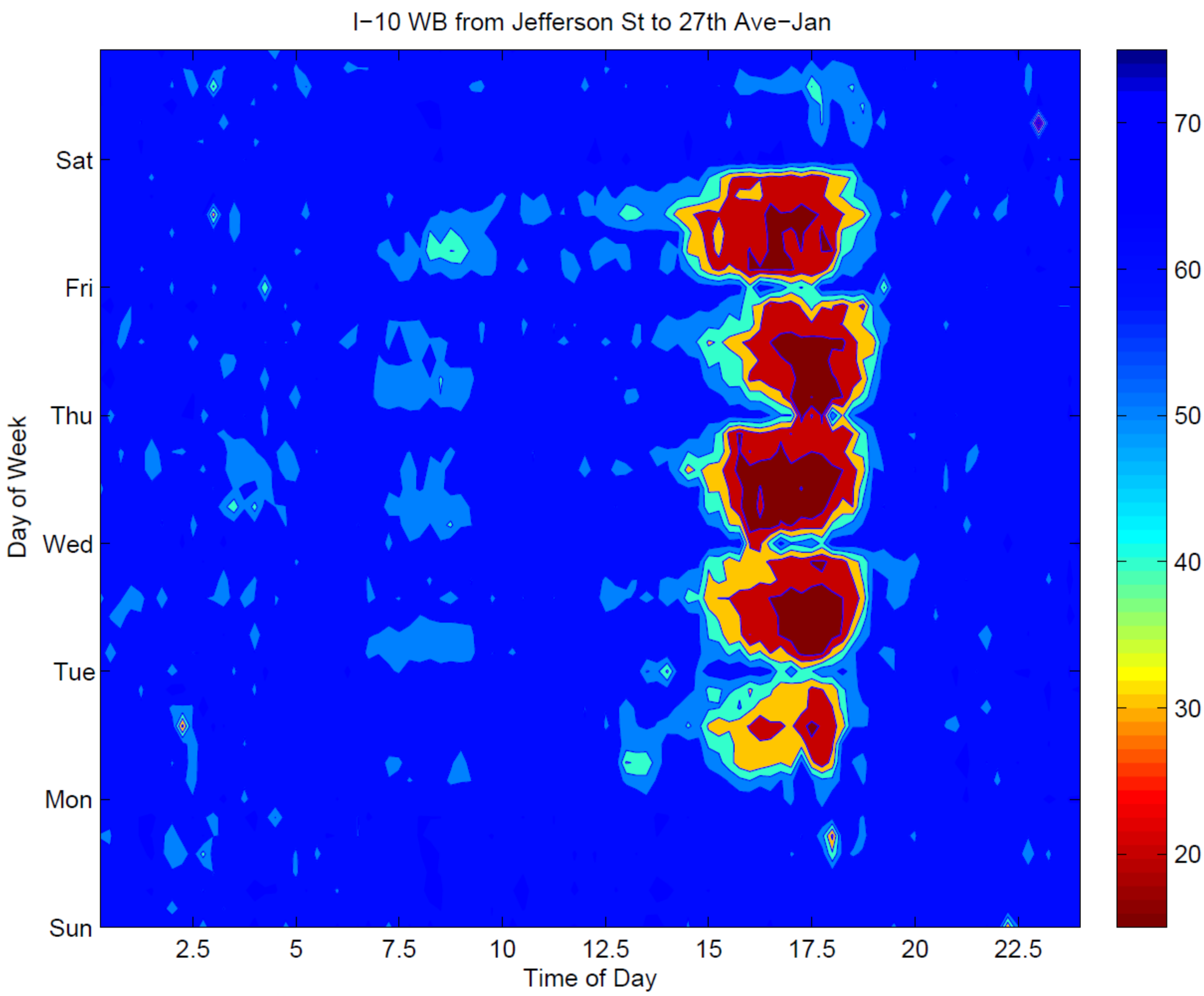

Figure 6: Speed contour (heat) map on a selected bottleneck corridor

2) Review the bottleneck's contour map to confirm the position and starting and ending points of the bottleneck. Based on the plots and the following segmentation guidelines, make a decision about whether to truncate/combine/modify the bottleneck:
   - In most cases, a freeway segment will include multiple entrance and exit ramps.
   - Freeway segment endpoints are typically entrance or exit ramps from/to another freeway or major cross street because this is where roadway characteristics, traffic levels, and congestion patterns are most likely to change.

- Freeway segments in dense, built-up areas typically range from 3 to 5 miles in length. These segments are also likely to have more frequent ramp access points.
- Freeway segments in less dense, suburban or exurban areas typically range from 5 to 10 miles in length. These segments are likely to have less frequent ramp access.

3) Review the locations of all bottleneck corridors in the region, and add/break a few new bottlenecks based on interactions between the bottlenecks.

With this “art” part of the process, the combination of “science” and “art” concludes the task of bottleneck identification with a total of 53 bottlenecks identified, as shown in Figure 7.

Freeway Bottlenecks (53)

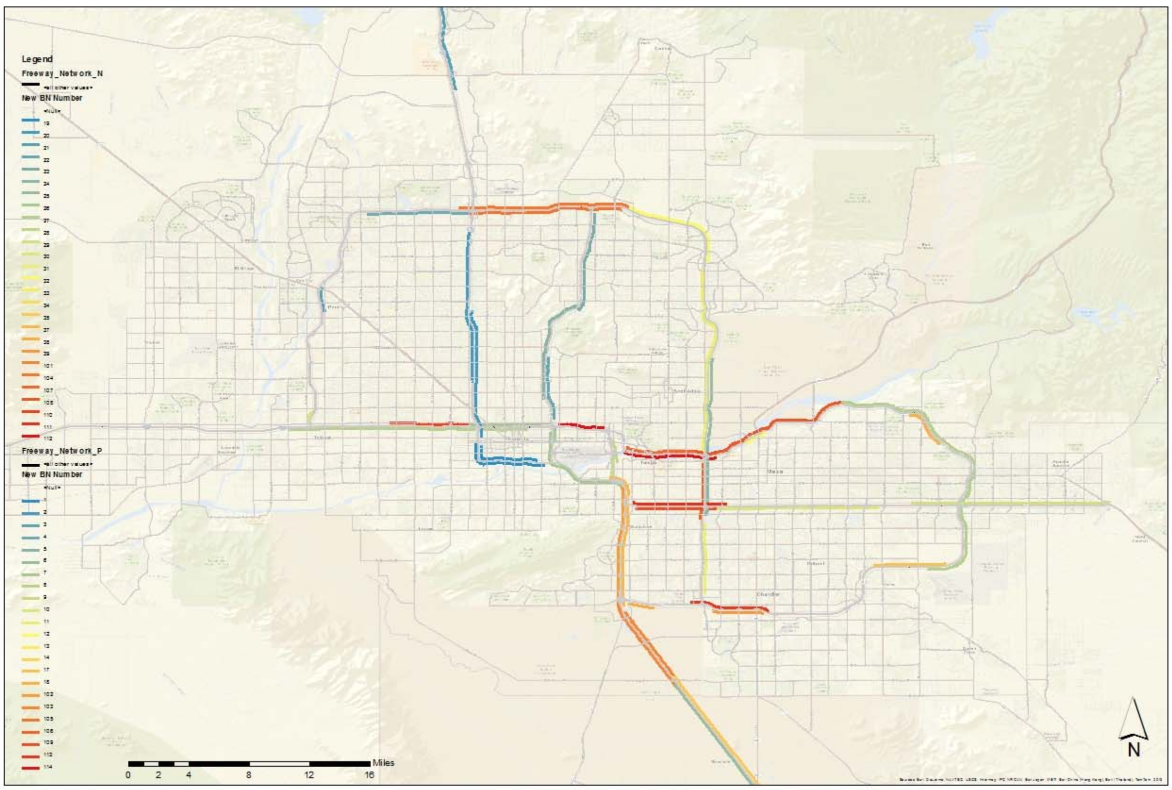

Figure 7: Updated map of bottlenecks identified (53 bottlenecks)

4. Measuring Bottlenecks in the MAG Region

The identified bottlenecks are not necessarily the true bottlenecks because their congestion/delay characteristics have not been quantitatively visited; therefore, they are called bottleneck candidates. In this step, a series of congestion measures are computed for each bottleneck candidate, and only the ones showing clear congestion problems remain as bottlenecks for further investigation and evaluation. Figure 8 explains the work flow of data preparation and bottleneck measurement.

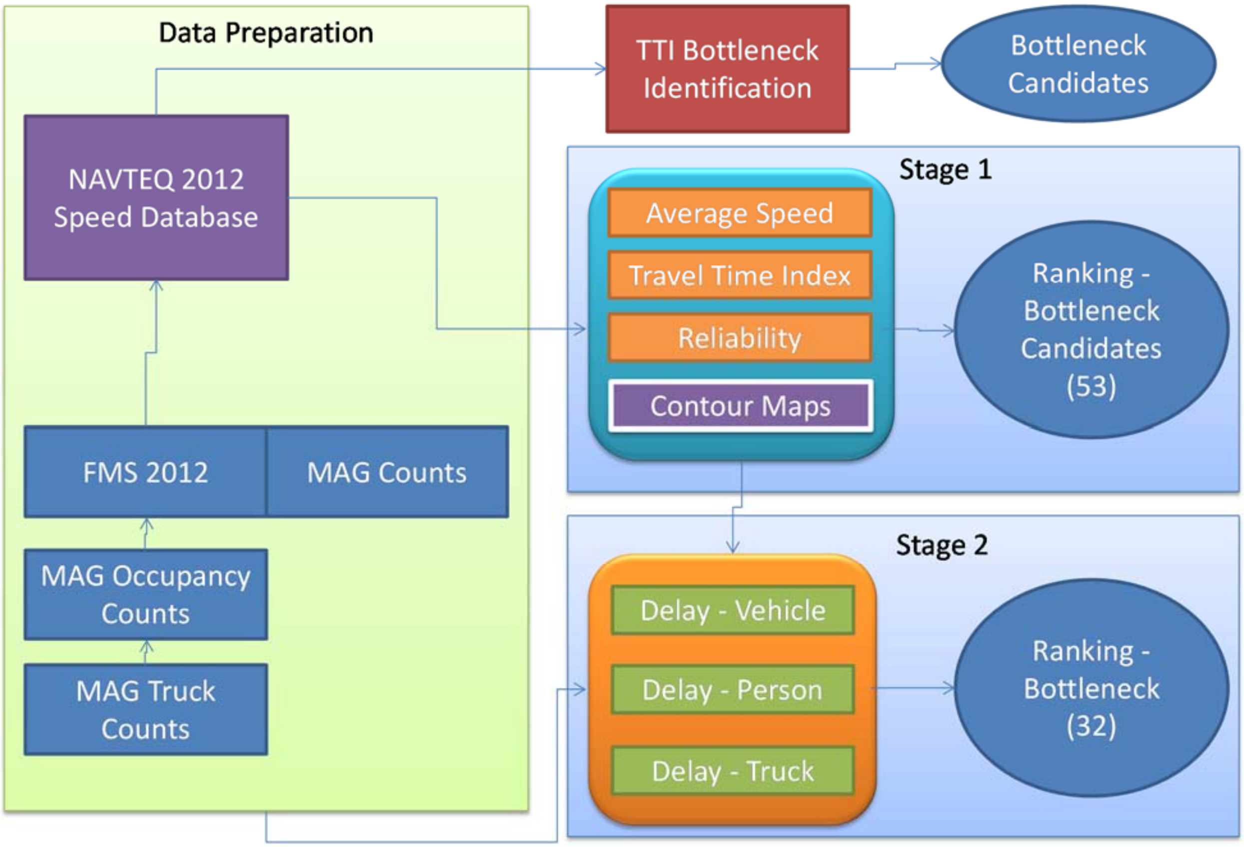

Figure 8: Bottleneck measurement work flow

Data Preparation

Several datasets are required to conduct the bottleneck congestion measurement analysis:

- *Speed database*—The TMC-based historical speed database provides 15-minute average speed by weekday and by month for any TMC link.
- *Volume database*—The Arizona Department of Transportation's freeway automatic traffic recorder (ATR) database and MAG's short-term counts are combined into a TMC-based volume database. Using geographical information system (GIS) spatial analysis tools, data aggregation, and imputation, the volume database reports average traffic volume by 15-minute intervals for a weekday and a month at the TMC level. Seasonal variation factors are applied in imputing short-term counts into this database.
- *Vehicle occupancy database*—The vehicle occupancy database obtained from the MAG 2012 vehicle occupancy study is converted to a TMC-based vehicle occupancy database. Using GIS spatial analysis tools, data aggregation, and imputation, the vehicle occupancy database reports average persons per vehicle by 15-minute intervals for a weekday and a month on a TMC link.
- *Truck (freight) database*—The MAG short-term vehicle classification counts are converted to a heavy-truck database and a medium-truck database; both are TMC based. Using GIS spatial analysis tools, data aggregation, and imputation, the truck databases report average heavy- or medium-truck percentage by 15-minute intervals for a weekday and a month on a TMC link.

These databases are indexed by TMC and formatted uniformly to allow ease of computation in congestion measurement and analysis.

Two-Stage Bottleneck Measurement

In a two-stage process, all bottleneck candidates are studied and ranked in stage 1 using the NAVTEQ 2012 speed database only, and only the higher ranking candidates (true congested bottlenecks) enter stage 2, which uses all speed/count/vehicle occupancy/truck databases. Different congestion measures are calculated and analyzed in each stage. Table 1 specifies the congestion dimensions and individual measures involved in each stage.

Table 1: Bottleneck measurement content

Dimension	Definition	Typical Measure	Itemized Measure	Calculating Measure	Stage
Duration	The quantity of time that congestion affects the travel system.	Hours of daily congestion	Hours of daily normal congestion (<50mph)	Total time when avg speed is lower than 50mph	1
			Hours of daily severe congestion (<35mph)	Total time when avg speed is lower than 35mph	1
Extent	The quantity of persons, vehicles, or roadways affected by congestion.	% road-miles with congestion	normal congestion	TMC under 50mph / total TMC	2
			severe congestion	TMC under 35mph / total TMC	2
		% travel in congestion	normal congestion	Flow on TMC under 50mph / total flow	2
			severe congestion	Flow on TMC under 35mph / total flow	2
Intensity	The severity level (or "pain level") of congestion.	Peak period speed	by 15-min	Avg speed on BN (weighted by TMC length)	1
			by peak period	Avg speed on BN (weighted by TMC length) for the entire peak period	1
		Travel Time Index	by 15-min	TT/Free-flow TT on BN	1
			by peak period	Average TT/Free-flow TT on BN	1
		Travel Time	by 15-min	TT on BN	1
			by peak period	Average TT on BN	1
Reliability	The degree of consistency (or lack thereof) in congestion, as measured from day-to-day and/or across different times of the day.	Planning time index	by 15-min	95% Slowest TT/free-flow TT on BN	1
			by peak period	Weighted by VMT	2
		Buffer index	by 15-min	95% Slowest TT/free-flow TT-1 on BN	1
			by peak period	Weighted by VMT	2
		% trips with on-time arrival	by peak period	(1- flow under normal congestion / total flow in that period) %	2
		% of days congested	by 15-min	(# of Days BN under normal congestion / total # of weekday) % (<50mph)	1
			by 15-min	(# of Days BN under severe congestion / total # of weekday) % (<35mph)	1
		% of days congested	by peak period	(# of Days BN peak period avg speed under normal congestion / total # of weekday) %	1

Dimension	Definition	Typical Measure	Itemized Measure	Calculating Measure	Stage
				(<50mph)	
			by peak period	(# of Days BN peak period avg speed under normal congestion / total # of weekday) % (<35mph)	1
Multiple Dimensions and Others	Duration, Extent and Intensity	Total delay per mile		Sum of delay divided by segment length	2
		Total delay	by peak period	Sum of delay per vehicle on BN	2
		VMT	by peak period	Total VMT under congestion	2
		PMT	by peak period	Total PMT under congestion	2
Freight/Truck	All above measures on medium and heavy trucks	multiple	multiple	multiple	2

The higher the ranking score is, the more congested this bottleneck corridor is. As shown in Table 2, the bottleneck candidates are ranked in descending order per score. As a screening process, stage 1 investigates bottleneck congestion using the speed-only database. The total ranking score in Table 2 solely reflects the bottleneck's congestion condition based only on NAVTEQ historical speed. The bottlenecks ranked in the lower part of the table do not show clear delay or slowdown in traffic; thus, only the bottlenecks in the top part (32 of them, highlighted in light red) are studied in stage 2.

Table 2: Ranking of bottleneck candidates from stage 1

New BN Number	ROUTE	New_DIRECTION	New_BN_TAIL	New_BN_HEAD	From	To	Length	Annual AM Spd	Annual AM TTI	Annual AM <50 Interval	Annual PM Spd	Annual PM TTI	Annual PM <50 Interval	**Total Ranking Score**
112	Loop 202 (Red Mt)	Outer	115P04229	115P04232	44th St	24th St	3.054274	499	522	499	573	597	503	3193
8	I-10	EB	115N04208	115N04195	107th Ave	11th St	15.92751	622	622	624	381	374	480	3103
1	I-17	SB	115N04104	115N04098	Van Buren St	I 10 Fwy	7.516541	597	446	550	503	403	444	2943
37	I-10	WB	115P05165	115P04184	L202 Red Mt	48th St	10.67224	575	604	599	369	346	382	2875
7	I-10	EB	115N04192	115N04183	Roosevelt St	Southern Ave	7.859196	353	373	320	583	602	605	2836
25	Loop 101	Outer	115P04163	115P04168	Loop 202 Red Mc	Mcdonald Dr	7.131852	510	559	552	368	404	433	2826
2	I-17	SB	115N04119	115N04110	Union Hills	Camelback	11.85137	594	576	611	401	301	292	2775
9	SR-143	SB	115N04235	115N04234	Sky Harbor Blvd	I 10 Fwy	1.811037	523	45	484	598	534	499	2683
22	SR-51	NB	115P04143	115P04147	McDowell Rd	Bethany Home R	4.96529	408	335	291	535	541	523	2633
20	I-17	NB	115P04106	115P04114	Adams St	Dunlap Ave	10.24849	404	180	304	575	550	606	2619
106	Loop 101	Inner	115N04161	115N04157	Loop 202 Red Mt	Baseline Rd	4.529985	259	398	196	563	591	570	2577
31	Loop 101	Outer	115P04365	115P04369	L202 Santan	Guadalupe Rd	5.579278	555	579	533	322	279	293	2561
26	I-10	WB	115P04192	115P04198	Jefferson St	27th Ave	6.672364	281	134	256	624	622	612	2529
111	US-60	EB	115P04240	115P04246	Priest Dr	Dobson Rd	8.50836	340	394	304	486	470	472	2466
11	Loop 101	Inner	115N04162	115N04370	Thunderbird Rd	Loop 202 Red Mc	15.95642	202	286	368	488	523	598	2465
24	Loop 101	Outer	115P04158	115P04162	US 60	Loop 202 Red Mc	5.437665	488	566	504	247	386	209	2400
5	SR-51	SB	115N04150	115N04144	Shea Blvd	Indian School Rd	8.132051	521	514	567	349	187	261	2399
105	Loop 101	Inner	115N04140	115N04378	I 17 Fwy	Tatum Blvd	10.18627	560	582	583	215	160	208	2308
110	I-10	WB	115P04199	115P04203	27th Ave	59th Ave	5.246018	281	227	88	566	572	572	2306
109	US-60	WB	115N04245	115N04241	Dobson Rd	Priest Dr	5.289279	469	500	505	287	211	319	2291
28	SR-143	NB	115P04236	115P04238	University Dr	Sky Harbor Blvd	2.97633	468	376	364	454	330	298	2290
30	Loop 101	Outer	115P04272	115P04271	Thomas Rd	I-10 Fwy	1.779381	528	446	383	451	236	216	2260
19	I-17	NB	115P04100	115P04104	16th St	Jefferson St	4.911584	432	33	220	560	469	542	2256
104	Loop 101	Outer	115P04378	115P04139	56th St	35th Ave	11.3452	150	351	206	455	521	530	2213
102	I-10	EB	115N04182	115N05165	Southern Ave	L202	9.059414	243	266	184	485	480	503	2161
10	US-60	WB	115N04253	115N04246	Higley Rd	Dobson Rd	10.76985	449	494	530	230	166	144	2013
23	SR-51	NB	115P04151	115P05162	Mountain View R	L101	9.551312	283	239	302	383	402	400	2009
4	Loop 101	Inner	115N04135	115N04139	75th Ave	I 17 Fwy	6.717976	437	484	427	176	323	68	1915
113	Loop 202 (Santan)	Inner	115N10862	115N07770	McQueen Rd	L101	5.330933	343	496	411	185	396	45	1876
39	Loop 202	Outer	115P10862	115P10860	Dobson Rd	Arizona Ave	3.309823	252	159	84	439	466	430	1830
107	Loop 202	Outer	115P04225	115P04222	L101	Priest Dr	4.833079	462	446	469	271	51	124	1823
114	Loop 202 (Red Mt)	Inner	115N04224	115N04221	Sky Harbor Blvd	L101	6.038916	219	293	38	385	410	398	1743
18	Loop 202	Inner	115N10873	115N10875	Mcdowell Rd	Power Rd	3.321337	438	451	469	113	110	157	1738
108	Loop 202	Outer	115P04221	115P04418	Gilbert Rd	L101	11.24578	274	313	410	250	127	185	1559
32	Loop 101	Outer	115P04372	115P04379	Thunderbird Rd	56th St	7.896399	162	126	210	353	278	365	1494
38	Loop 202	Outer	115P07768	115P07767	I-10 Fwy	Kyrene Rd	3.151213	318	118	354	225	48	352	1415
27	Loop 202	Outer	115P04417	115P11115	Greenfield Rd	Warner Rd	20.93084	169	232	333	178	182	263	1357
101	I-10	WB	115P04175	115P04176	Riggs Rd	L202	6.071977	114	275	70	263	364	263	1349
3	Loop 101	Inner	115N04129	115N04130	Olive Ave	Grand Ave	1.98075	289	368	65	244	254	54	1274
36	I-8	EB	115P05147	115P05150	SR387	SR87	14.00594	94	390	207	87	329	166	1273
29	US-60	EB	115P04256	115P04264	Power Rd	Apache Trl	13.10527	198	167	213	218	181	286	1263
103	I-10	EB	115N07213	115N04174	L202	Riggs Rd	7.710565	133	122	79	247	307	360	1248
12	Loop 202	Inner	115N04218	115N04420	McKellips Rd	Gilbert Rd	1.629468	393	60	358	203	39	106	1159
15	I-8	WB	115N05143	115N05140	SR 587 / Casa Bla	SR 187 / Pinal Av	43.67808	37	272	144	63	300	138	954
14	I-10	EB	115N04674	115N04673	Sunshine Blvd	Picacho Hwy	2.888962	85	333	54	68	260	53	853
17	Loop 202	Inner	115N10868	115N10869	Power Rd	Power Rd	4.744813	187	168	109	156	105	80	805
6	I-10	EB	115N04173	115N04677	Riggs Rd	Sunland Gin Rd	39.18795	104	136	127	102	163	162	794
35	I-10	WB	115P04682	115P04174	Mccartney Rd	Riggs Rd	27.52209	52	189	75	72	241	164	793
21	I-17	NB	115P04125	115P04667	AZ-74	Yavapai county li	22.59193	66	98	117	67	133	190	671
34	I-10	WB	115P04678	115P04679	Sunland Gin Rd	AZ 84	2.557911	70	133	53	84	141	60	541
13	I-10	EB	115N04669	115N04668	Sasco Rd	Tangerine Rd	6.663736	34	45	110	19	45	28	281
33	I-10	WB	115P04672	115P04674	Picacho Hwy	Picacho Peak	10.48425	12	15	21	17	26	48	139

Stage 2

In this stage, four databases (speed, volume, vehicle occupancy, and truck) are used to measure the bottlenecks. The following congestion measures are primarily used in ranking and prioritizing the 32 bottlenecks in stage 2:

- The delay is the actual travel time minute the free-flow travel time at a TMC.
- The annual delay per vehicle is the sum of delay per vehicle in hours at a bottleneck.
- The annual delay per person is the annual delay per vehicle multiplied by the average vehicle occupancy rate.
- The annual delay per medium truck is the annual delay per vehicle multiplied by the medium-truck percentage.
- The annual delay per heavy truck is the annual delay per vehicle multiplied by the heavy-truck percentage.

Any of the calculated measures can be used to rank the 32 bottlenecks from top to bottom. For instance, Table 3 shows the bottleneck ranking according to the annual daily delay per vehicle. The map in Figure 9 illustrates the bottleneck ranking per annual daily delay per vehicle, with the top five highlighted in red.

Table 3: Bottleneck ranking in stage 2 of daily delay per vehicle

					Delay per Vehicle			Delay per Person			Delay Per Heavy Truck V			Delay Per Medium Truck V			Annual Average Speed			Annual Average TTI			Annual <50mph interval		
New BN Number	ROUTE	Direction	From	To	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank
26	I-10	WB	Jefferson St	27th Ave	1	19	1	1	19	1	4	18	2	1	23	1	13	25	1	18	30	1	11	25	1
8	I-10	EB	107th Ave	11th St	2	1	9	2	1	8	1	1	5	2	1	6	4	1	21	2	1	21	1	1	13
7	I-10	EB	Roosevelt St	Southern Ave	3	18	2	3	18	2	2	15	1	3	18	2	11	21	3	4	20	2	8	20	3
37	I-10	WB	L202	48th St	4	2	20	4	2	19	3	2	13	4	2	18	9	4	22	7	2	22	6	3	20
11	Loop 101	Inner	Thunderbird Rd	Loop 202 Red Mount	5	16	3	5	16	3	13	23	7	10	19	5	26	31	11	15	24	9	7	18	4
106	Loop 101	Inner	Loop 202 Red Mount	Baseline Rd	6	22	4	6	22	5	10	20	11	13	21	8	19	27	7	3	17	4	18	28	6
112	Loop 202 (Red Mt)	Outer	44th St	24th St	7	12	5	7	12	4	11	12	10	15	14	9	3	11	5	1	8	3	2	12	10
20	I-17	NB	Adams St	Dunlap Ave	8	23	6	8	23	6	8	22	4	7	22	3	7	20	4	21	28	6	9	21	2
5	SR-51	SB	Shea Blvd	Indian School Rd	9	4	27	10	4	27	19	8	26	14	6	28	16	9	24	25	9	29	12	5	25
2	I-17	SB	Union Hills	Camelback	10	3	23	12	3	23	7	4	22	16	8	25	5	3	18	9	5	25	10	2	24
25	Loop 101	Outer	Loop 202 Red Mount	Mcdonald Dr	11	7	18	11	6	18	17	10	23	17	9	22	14	10	23	5	7	16	4	6	16
110	I-10	WB	27th Ave	59th Ave	12	30	7	9	30	7	5	28	3	6	30	4	17	25	6	17	27	5	26	30	5
105	Loop 101	Inner	I 17 Fwy	Tatum Blvd	13	5	29	14	5	29	16	6	30	12	5	30	20	5	30	20	3	31	16	4	28
1	I-17	SB	Van Buren St	I 10 Fwy	14	10	12	13	10	12	6	3	6	9	7	11	2	2	10	14	14	17	3	7	15
23	SR-51	NB	Mountain View Rd	L101	15	29	8	15	29	9	24	29	15	8	26	7	28	24	20	28	26	18	22	23	18
10	US-60	WB	Higley Rd	Dobson Rd	16	6	25	16	7	25	15	5	25	5	3	20	27	16	29	27	12	30	24	9	29
31	Loop 101	Outer	L202	Guadalupe Rd	17	8	24	17	8	24	18	9	24	24	13	24	15	6	25	13	4	26	13	8	23
22	SR-51	NB	McDowell Rd	Bethany Home Rd	18	25	10	18	25	10	20	27	12	18	25	10	10	19	9	10	22	7	15	24	9
109	US-60	WB	Dobson Rd	Priest Dr	19	9	22	19	9	22	12	7	21	11	4	21	21	13	26	22	10	28	14	10	21
102	I-10	EB	Southern Ave	L202	20	20	14	20	20	14	9	19	8	19	20	13	24	29	13	19	25	11	23	29	10
104	Loop 101	Outer	56th St	35th Ave	21	27	11	21	27	11	27	30	16	27	29	15	30	32	14	11	21	10	20	27	8
9	SR-143	SB	Sky Harbor Blvd	I 10 Fwy	22	24	13	22	24	13	23	25	14	20	24	14	1	8	2	30	31	8	5	13	12
24	Loop 101	Outer	US 60	Loop 202 Red Mount	23	11	26	23	11	26	22	11	28	22	10	29	22	12	28	6	6	20	21	11	27
28	SR-143	NB	University Dr	Sky Harbor Blvd	24	17	21	24	17	21	21	21	18	21	17	16	12	14	15	23	19	23	25	19	22
111	US-60	EB	Priest Dr	Dobson Rd	25	26	16	25	26	16	25	26	17	28	27	17	18	23	12	12	18	12	17	21	14
39	Loop 202	Outer	Alma School	Dobson Rd	26	31	17	26	31	17	29	31	19	29	31	19	25	28	17	29	29	14	29	31	17
19	I-17	NB	16th St	Jefferson St	27	28	15	27	28	15	14	24	9	23	28	12	6	18	8	31	32	13	19	26	7
107	Loop 202	Outer	Priest Dr	L101	28	13	28	28	13	28	26	13	27	25	12	26	23	15	27	32	14	32	28	14	30
114	Loop 202 (Red Mt)	Inner	Sky Harbor Blvd	L101	29	32	19	29	32	20	31	32	20	32	32	23	31	30	19	24	23	15	32	32	19
113	Loop 202 (Santan)	Inner	McQueen Rd	L101	30	14	32	30	14	32	30	16	32	31	15	32	32	22	31	8	11	19	31	16	32
4	Loop 101	Inner	75th Ave	I 17 Fwy	31	15	31	31	15	31	28	14	31	26	11	31	29	17	32	16	13	24	30	15	31
30	Loop 101	Outer	Thomas Rd	I-10 Fwy	32	21	30	32	21	30	32	17	29	30	16	27	7	7	16	26	14	27	27	17	26

Freeway Bottlenecks

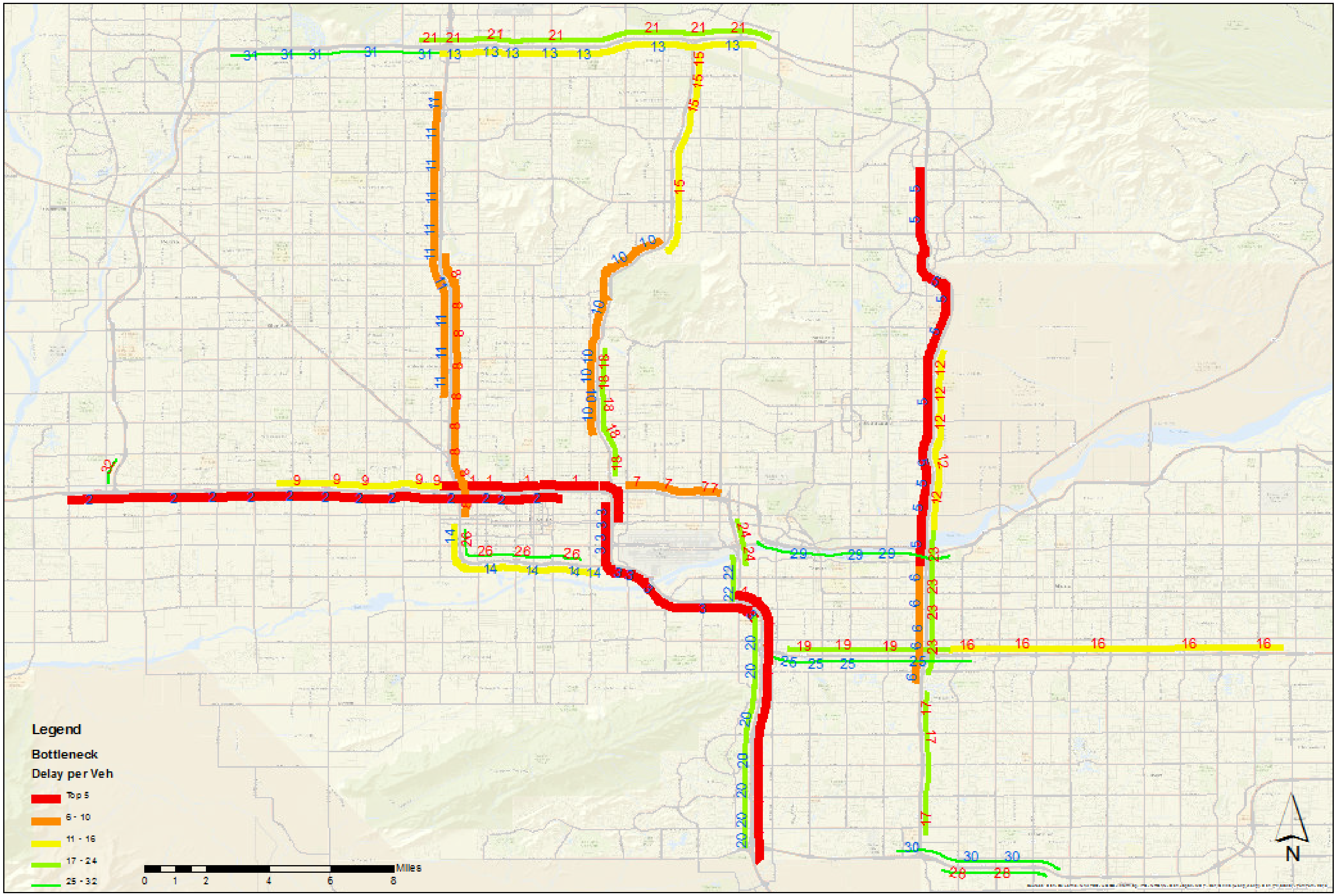

Figure 9: Map of 32 bottlenecks ranked from 1 to 32 for delay per vehicle

Tables 4 and 5 show the ranking of delay per vehicle for the bottlenecks in the AM or PM, respectively.

Table 4: Bottleneck ranking of delay per vehicle in the AM

					Delay per Vehicle			Delay per Person			Delay Per Heavy Truck V			Delay Per Medium Truck V			Annual Average Speed			Annual Average TTI			Annual <50mph interval		
New BN Number	ROUTE	Direction	From	To	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank
8	I-10	EB	107th Ave	11th St	2	1	9	2	1	8	1	1	5	2	1	6	4	1	21	2	1	21	1	1	13
37	I-10	WB	L202	48th St	4	2	20	4	2	19	3	2	13	4	2	18	9	4	22	7	2	22	6	3	20
2	I-17	SB	Union Hills	Camelback	10	3	23	12	3	23	7	4	22	16	8	25	5	3	18	9	5	25	10	2	24
5	SR-51	SB	Shea Blvd	Indian School Rd	9	4	27	10	4	27	19	8	26	14	6	28	16	9	24	25	9	29	12	5	25
105	Loop 101	Inner	I 17 Fwy	Tatum Blvd	13	5	29	14	5	29	16	6	30	12	5	30	20	5	30	20	3	31	16	4	28
10	US-60	WB	Higley Rd	Dobson Rd	16	6	25	16	7	25	15	5	25	5	3	20	27	16	29	27	12	30	24	9	29
25	Loop 101	Outer	Loop 202 Red Mounta	Mcdonald Dr	11	7	18	11	6	18	17	10	23	17	9	22	14	10	23	5	7	16	4	6	16
31	Loop 101	Outer	L202	Guadalupe Rd	17	8	24	17	8	24	18	9	24	24	13	24	15	6	25	13	4	26	13	8	23
109	US-60	WB	Dobson Rd	Priest Dr	19	9	22	19	9	22	12	7	21	11	4	21	21	13	26	22	10	28	14	10	21
1	I-17	SB	Van Buren St	I 10 Fwy	14	10	12	13	10	12	6	3	6	9	7	11	2	2	10	14	14	17	3	7	15
24	Loop 101	Outer	US 60	Loop 202 Red Mount	23	11	26	23	11	26	22	11	28	22	10	29	22	12	28	6	6	20	21	11	27
112	Loop 202 (Red Mt)	Outer	44th St	24th St	7	12	5	7	12	4	11	12	10	15	14	9	3	11	5	1	8	3	2	12	10
107	Loop 202	Outer	Priest Dr	L101	28	13	28	28	13	28	26	13	27	25	12	26	23	15	27	32	14	32	28	14	30
113	Loop 202 (Santan)	Inner	McQueen Rd	L101	30	14	32	30	14	32	30	16	32	31	15	32	32	22	31	8	11	19	31	16	32
4	Loop 101	Inner	75th Ave	I 17 Fwy	31	15	31	31	15	31	28	14	31	26	11	31	29	17	32	16	13	24	30	15	31
11	Loop 101	Inner	Thunderbird Rd	Loop 202 Red Mount	5	16	3	5	16	3	13	23	7	10	19	5	26	31	11	15	24	9	7	18	4
28	SR-143	NB	University Dr	Sky Harbor Blvd	24	17	21	24	17	21	21	21	18	21	17	16	12	14	15	23	19	23	25	19	22
7	I-10	EB	Roosevelt St	Southern Ave	3	18	2	3	18	2	2	15	1	3	18	2	11	21	3	4	20	2	8	20	3
26	I-10	WB	Jefferson St	27th Ave	1	19	1	1	19	1	4	18	2	1	23	1	13	25	1	18	30	1	11	25	1
102	I-10	EB	Southern Ave	L202	20	20	14	20	20	14	9	19	8	19	20	13	24	29	13	19	25	11	23	29	10
30	Loop 101	Outer	Thomas Rd	I-10 Fwy	32	21	30	32	21	30	32	17	29	30	16	27	7	7	16	26	14	27	27	17	26
106	Loop 101	Inner	Loop 202 Red Mounta	Baseline Rd	6	22	4	6	22	5	10	20	11	13	21	8	19	27	7	3	17	4	18	28	6
20	I-17	NB	Adams St	Dunlap Ave	8	23	6	8	23	6	8	22	4	7	22	3	7	20	4	21	28	6	9	21	2
9	SR-143	SB	Sky Harbor Blvd	I 10 Fwy	22	24	13	22	24	13	23	25	14	20	24	14	1	8	2	30	31	8	5	13	12
22	SR-51	NB	McDowell Rd	Bethany Home Rd	18	25	10	18	25	10	20	27	12	18	25	10	10	19	9	10	22	7	15	24	9
111	US-60	EB	Priest Dr	Dobson Rd	25	26	16	25	26	16	25	26	17	28	27	17	18	23	12	12	18	12	17	21	14
104	Loop 101	Outer	56th St	35th Ave	21	27	11	21	27	11	27	30	16	27	29	15	30	32	14	11	21	10	20	27	8
19	I-17	NB	16th St	Jefferson St	27	28	15	27	28	15	14	24	9	23	28	12	6	18	8	31	32	13	19	26	7
23	SR-51	NB	Mountain View Rd	L101	15	29	8	15	29	9	24	29	15	8	26	7	28	24	20	28	26	18	22	23	18
110	I-10	WB	27th Ave	59th Ave	12	30	7	9	30	7	5	28	3	6	30	4	17	25	6	17	27	5	26	30	5
39	Loop 202	Outer	Alma School	Dobson Rd	26	31	17	26	31	17	29	31	19	29	31	19	25	28	17	29	29	14	29	31	17
114	Loop 202 (Red Mt)	Inner	Sky Harbor Blvd	L101	29	32	19	29	32	20	31	32	20	32	32	23	31	30	19	24	23	15	32	32	19

Table 5: Bottleneck ranking of delay per vehicle in the PM

					Delay per Vehicle			Delay per Person			Delay Per Heavy Truck V			Delay Per Medium Truck V			Annual Average Speed			Annual Average TTI			Annual <50mph interval		
New BN Number	ROUTE	Direction	From	To	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank
26	I-10	WB	Jefferson St	27th Ave	1	19	1	1	19	1	4	18	2	1	23	1	13	25	1	18	30	1	11	25	1
7	I-10	EB	Roosevelt St	Southern Ave	3	18	2	3	18	2	2	15	1	3	18	2	11	21	3	4	20	2	8	20	3
11	Loop 101	Inner	Thunderbird Rd	Loop 202 Red Mount	5	16	3	5	16	3	13	23	7	10	19	5	26	31	11	15	24	9	7	18	4
106	Loop 101	Inner	Loop 202 Red Mounta	Baseline Rd	6	22	4	6	22	5	10	20	11	13	21	8	19	27	7	3	17	4	18	28	6
112	Loop 202 (Red Mt)	Outer	44th St	24th St	7	12	5	7	12	4	11	12	10	15	14	9	3	11	5	1	8	3	2	12	10
20	I-17	NB	Adams St	Dunlap Ave	8	23	6	8	23	6	8	22	4	7	22	3	7	20	4	21	28	6	9	21	2
110	I-10	WB	27th Ave	59th Ave	12	30	7	9	30	7	5	28	3	6	30	4	17	25	6	17	27	5	26	30	5
23	SR-51	NB	Mountain View Rd	L101	15	29	8	15	29	9	24	29	15	8	26	7	28	24	20	28	26	18	22	23	18
8	I-10	EB	107th Ave	11th St	2	1	9	2	1	8	1	1	5	2	1	6	4	1	21	2	1	21	1	1	13
22	SR-51	NB	McDowell Rd	Bethany Home Rd	18	25	10	18	25	10	20	27	12	18	25	10	10	19	9	10	22	7	15	24	9
104	Loop 101	Outer	56th St	35th Ave	21	27	11	21	27	11	27	30	16	27	29	15	30	32	14	11	21	10	20	27	8
1	I-17	SB	Van Buren St	I 10 Fwy	14	10	12	13	10	12	6	3	6	9	7	11	2	2	10	14	14	17	3	7	15
9	SR-143	SB	Sky Harbor Blvd	I 10 Fwy	22	24	13	22	24	13	23	25	14	20	24	14	1	8	2	30	31	8	5	13	12
102	I-10	EB	Southern Ave	L202	20	20	14	20	20	14	9	19	8	19	20	13	24	29	13	19	25	11	23	29	10
19	I-17	NB	16th St	Jefferson St	27	28	15	27	28	15	14	24	9	23	28	12	6	18	8	31	32	13	19	26	7
111	US-60	EB	Priest Dr	Dobson Rd	25	26	16	25	26	16	25	26	17	28	27	17	18	23	12	12	18	12	17	21	14
39	Loop 202	Outer	Alma School	Dobson Rd	26	31	17	26	31	17	29	31	19	29	31	19	25	28	17	29	29	14	29	31	17
25	Loop 101	Outer	Loop 202 Red Mounta	Mcdonald Dr	11	7	18	11	6	18	17	10	23	17	9	22	14	10	23	5	7	16	4	6	16
114	Loop 202 (Red Mt)	Inner	Sky Harbor Blvd	L101	29	32	19	29	32	20	31	32	20	32	32	23	31	30	19	24	23	15	32	32	19
37	I-10	WB	L202	48th St	4	2	20	4	2	19	3	2	13	4	2	18	9	4	22	7	2	22	6	3	20
28	SR-143	NB	University Dr	Sky Harbor Blvd	24	17	21	24	17	21	21	21	18	21	17	16	12	14	15	23	19	23	25	19	22
109	US-60	WB	Dobson Rd	Priest Dr	19	9	22	19	9	22	12	7	21	11	4	21	21	13	26	22	10	28	14	10	21
2	I-17	SB	Union Hills	Camelback	10	3	23	12	3	23	7	4	22	16	8	25	5	3	18	9	5	25	10	2	24
31	Loop 101	Outer	L202	Guadalupe Rd	17	8	24	17	8	24	18	9	24	24	13	24	15	6	25	13	4	26	13	8	23
10	US-60	WB	Higley Rd	Dobson Rd	16	6	25	16	7	25	15	5	25	5	3	20	27	16	29	27	12	30	24	9	29
24	Loop 101	Outer	US 60	Loop 202 Red Mount	23	11	26	23	11	26	22	11	28	22	10	29	22	12	28	6	6	20	21	11	27
5	SR-51	SB	Shea Blvd	Indian School Rd	9	4	27	10	4	27	19	8	26	14	6	28	16	9	24	25	9	29	12	5	25
107	Loop 202	Outer	Priest Dr	L101	28	13	28	28	13	28	26	13	27	25	12	26	23	15	27	32	14	32	28	14	30
105	Loop 101	Inner	I 17 Fwy	Tatum Blvd	13	5	29	14	5	29	16	6	30	12	5	30	20	5	30	20	3	31	16	4	28
30	Loop 101	Outer	Thomas Rd	I-10 Fwy	32	21	30	32	21	30	32	17	29	30	16	27	7	7	16	26	14	27	27	17	26
4	Loop 101	Inner	75th Ave	I 17 Fwy	31	15	31	31	15	31	28	14	31	26	11	31	29	17	32	16	13	24	30	15	31
113	Loop 202 (Santan)	Inner	McQueen Rd	L101	30	14	32	30	14	32	30	16	32	31	15	32	32	22	31	8	11	19	31	16	32

Tables 6 and 7 show the ranking of delay per heavy truck and per medium truck, respectively.

Table 6: Bottleneck ranking of delay per heavy truck

					Delay per Vehicle			Delay per Person			Delay Per Heavy Truck V			Delay Per Medium Truck V			Annual Average Speed			Annual Average TTI			Annual <50mph interval		
New BN Number	ROUTE	Direction	From	To	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank
8	I-10	EB	107th Ave	11th St	2	1	9	2	1	8	1	1	5	2	1	6	4	1	21	2	1	21	1	1	13
7	I-10	EB	Roosevelt St	Southern Ave	3	18	2	3	18	2	2	15	1	3	18	2	11	21	3	4	20	2	8	20	3
37	I-10	WB	L202	48th St	4	2	20	4	2	19	3	2	13	4	2	18	9	4	22	7	2	22	6	3	20
26	I-10	WB	Jefferson St	27th Ave	1	19	1	1	19	1	4	18	2	1	23	1	13	25	1	18	30	1	11	25	1
110	I-10	WB	27th Ave	59th Ave	12	30	7	9	30	7	5	28	3	6	30	4	17	25	6	17	27	5	26	30	5
1	I-17	SB	Van Buren St	I 10 Fwy	14	10	12	13	10	12	6	3	6	9	7	11	2	2	10	14	14	17	3	7	15
2	I-17	SB	Union Hills	Camelback	10	3	23	12	3	23	7	4	22	16	8	25	5	3	18	9	5	25	10	2	24
20	I-17	NB	Adams St	Dunlap Ave	8	23	6	8	23	6	8	22	4	7	22	3	7	20	4	21	28	6	9	21	2
102	I-10	EB	Southern Ave	L202	20	20	14	20	20	14	9	19	8	19	20	13	24	29	13	19	25	11	23	29	10
106	Loop 101	Inner	Loop 202 Red Mount	Baseline Rd	6	22	4	6	22	5	10	20	11	13	21	8	19	27	7	3	17	4	18	28	6
112	Loop 202 (Red Mt)	Outer	44th St	24th St	7	12	5	7	12	4	11	12	10	15	14	9	3	11	5	1	8	3	2	12	10
109	US-60	WB	Dobson Rd	Priest Dr	19	9	22	19	9	22	12	7	21	11	4	21	21	13	26	22	10	28	14	10	21
11	Loop 101	Inner	Thunderbird Rd	Loop 202 Red Mount	5	16	3	5	16	3	13	23	7	10	19	5	26	31	11	15	24	9	7	18	4
19	I-17	NB	16th St	Jefferson St	27	28	15	27	28	15	14	24	9	23	28	12	6	18	8	31	32	13	19	26	7
10	US-60	WB	Higley Rd	Dobson Rd	16	6	25	16	7	25	15	5	25	5	3	20	27	16	29	27	12	30	24	9	29
105	Loop 101	Inner	I 17 Fwy	Tatum Blvd	13	5	29	14	5	29	16	6	30	12	5	30	20	5	30	20	3	31	16	4	28
25	Loop 101	Outer	Loop 202 Red Mount	Mcdonald Dr	11	7	18	11	6	18	17	10	23	17	9	22	14	10	23	5	7	16	4	6	16
31	Loop 101	Outer	L202	Guadalupe Rd	17	8	24	17	8	24	18	9	24	24	13	24	15	6	25	13	4	26	13	8	23
5	SR-51	SB	Shea Blvd	Indian School Rd	9	4	27	10	4	27	19	8	26	14	6	28	16	9	24	25	9	29	12	5	25
22	SR-51	NB	McDowell Rd	Bethany Home Rd	18	25	10	18	25	10	20	27	12	18	25	10	10	19	9	10	22	7	15	24	9
28	SR-143	NB	University Dr	Sky Harbor Blvd	24	17	21	24	17	21	21	21	18	21	17	16	12	14	15	23	19	23	25	19	22
24	Loop 101	Outer	US 60	Loop 202 Red Mount	23	11	26	23	11	26	22	11	28	22	10	29	22	12	28	6	6	20	21	11	27
9	SR-143	SB	Sky Harbor Blvd	I 10 Fwy	22	24	13	22	24	13	23	25	14	20	24	14	1	8	2	30	31	8	5	13	12
23	SR-51	NB	Mountain View Rd	L101	15	29	8	15	29	9	24	29	15	8	26	7	28	24	20	28	26	18	22	23	18
111	US-60	EB	Priest Dr	Dobson Rd	25	26	16	25	26	16	25	26	17	28	27	17	18	23	12	12	18	12	17	21	14
107	Loop 202	Outer	Priest Dr	L101	28	13	28	28	13	28	26	13	27	25	12	26	23	15	27	32	14	32	28	14	30
104	Loop 101	Outer	56th St	35th Ave	21	27	11	21	27	11	27	30	16	27	29	15	30	32	14	11	21	10	20	27	8
4	Loop 101	Inner	75th Ave	I 17 Fwy	31	15	31	31	15	31	28	14	31	26	11	31	29	17	32	16	13	24	30	15	31
39	Loop 202	Outer	Alma School	Dobson Rd	26	31	17	26	31	17	29	31	19	29	31	19	25	28	17	29	29	14	29	31	17
113	Loop 202 (Santan)	Inner	McQueen Rd	L101	30	14	32	30	14	32	30	16	32	31	15	32	32	22	31	8	11	19	31	16	32
114	Loop 202 (Red Mt)	Inner	Sky Harbor Blvd	L101	29	32	19	29	32	20	31	32	20	32	32	23	31	30	19	24	23	15	32	32	19
30	Loop 101	Outer	Thomas Rd	I-10 Fwy	32	21	30	32	21	30	32	17	29	30	16	27	7	7	16	26	14	27	27	17	26

Table 7: Bottleneck ranking of delay per medium truck

					Delay per Vehicle			Delay per Person			Delay Per Heavy Truck V			Delay Per Medium Truck V			Annual Average Speed			Annual Average TTI			Annual <50mph interval		
New BN Number	ROUTE	Direction	From	To	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank	Daily Rank	AM rank	PM rank
26	I-10	WB	Jefferson St	27th Ave	1	19	1	1	19	1	4	18	2	1	23	1	13	25	1	18	30	1	11	25	1
8	I-10	EB	107th Ave	11th St	2	1	9	2	1	8	1	1	5	2	1	6	4	1	21	2	1	21	1	1	13
7	I-10	EB	Roosevelt St	Southern Ave	3	18	2	3	18	2	2	15	1	3	18	2	11	21	3	4	20	2	8	20	3
37	I-10	WB	L202	48th St	4	2	20	4	2	19	3	2	13	4	2	18	9	4	22	7	2	22	6	3	20
10	US-60	WB	Higley Rd	Dobson Rd	16	6	25	16	7	25	15	5	25	5	3	20	27	16	29	27	12	30	24	9	29
110	I-10	WB	27th Ave	59th Ave	12	30	7	9	30	7	5	28	3	6	30	4	17	25	6	17	27	5	26	30	5
20	I-17	NB	Adams St	Dunlap Ave	8	23	6	8	23	6	8	22	4	7	22	3	7	20	4	21	28	6	9	21	2
23	SR-51	NB	Mountain View Rd	L101	15	29	8	15	29	9	24	29	15	8	26	7	28	24	20	28	26	18	22	23	18
1	I-17	SB	Van Buren St	I 10 Fwy	14	10	12	13	10	12	6	3	6	9	7	11	2	2	10	14	14	17	3	7	15
11	Loop 101	Inner	Thunderbird Rd	Loop 202 Red Mount	5	16	3	5	16	3	13	23	7	10	19	5	26	31	11	15	24	9	7	18	4
109	US-60	WB	Dobson Rd	Priest Dr	19	9	22	19	9	22	12	7	21	11	4	21	21	13	26	22	10	28	14	10	21
105	Loop 101	Inner	I 17 Fwy	Tatum Blvd	13	5	29	14	5	29	16	6	30	12	5	30	20	5	30	20	3	31	16	4	28
106	Loop 101	Inner	Loop 202 Red Mount	Baseline Rd	6	22	4	6	22	5	10	20	11	13	21	8	19	27	7	3	17	4	18	28	6
5	SR-51	SB	Shea Blvd	Indian School Rd	9	4	27	10	4	27	19	8	26	14	6	28	16	9	24	25	9	29	12	5	25
112	Loop 202 (Red Mt)	Outer	44th St	24th St	7	12	5	7	12	4	11	12	10	15	14	9	3	11	5	1	8	3	2	12	10
2	I-17	SB	Union Hills	Camelback	10	3	23	12	3	23	7	4	22	16	8	25	5	3	18	9	5	25	10	2	24
25	Loop 101	Outer	Loop 202 Red Mount	Mcdonald Dr	11	7	18	11	6	18	17	10	23	17	9	22	14	10	23	5	7	16	4	6	16
22	SR-51	NB	McDowell Rd	Bethany Home Rd	18	25	10	18	25	10	20	27	12	18	25	10	10	19	9	10	22	7	15	24	9
102	I-10	EB	Southern Ave	L202	20	20	14	20	20	14	9	19	8	19	20	13	24	29	13	19	25	11	23	29	10
9	SR-143	SB	Sky Harbor Blvd	I 10 Fwy	22	24	13	22	24	13	23	25	14	20	24	14	1	8	2	30	31	8	5	13	12
28	SR-143	NB	University Dr	Sky Harbor Blvd	24	17	21	24	17	21	21	21	18	21	17	16	12	14	15	23	19	23	25	19	22
24	Loop 101	Outer	US 60	Loop 202 Red Mount	23	11	26	23	11	26	22	11	28	22	10	29	22	12	28	6	6	20	21	11	27
19	I-17	NB	16th St	Jefferson St	27	28	15	27	28	15	14	24	9	23	28	12	6	18	8	31	32	13	19	26	7
31	Loop 101	Outer	L202	Guadalupe Rd	17	8	24	17	8	24	18	9	24	24	13	24	15	6	25	13	4	26	13	8	23
107	Loop 202	Outer	Priest Dr	L101	28	13	28	28	13	28	26	13	27	25	12	26	23	15	27	32	14	32	28	14	30
4	Loop 101	Inner	75th Ave	I 17 Fwy	31	15	31	31	15	31	28	14	31	26	11	31	29	17	32	16	13	24	30	15	31
104	Loop 101	Outer	56th St	35th Ave	21	27	11	21	27	11	27	30	16	27	29	15	30	32	14	11	21	10	20	27	8
111	US-60	EB	Priest Dr	Dobson Rd	25	26	16	25	26	16	25	26	17	28	27	17	18	23	12	12	18	12	17	21	14
39	Loop 202	Outer	Alma School	Dobson Rd	26	31	17	26	31	17	29	31	19	29	31	19	25	28	17	29	29	14	29	31	17
30	Loop 101	Outer	Thomas Rd	I-10 Fwy	32	21	30	32	21	30	32	17	29	30	16	27	7	7	16	26	14	27	27	17	26
113	Loop 202 (Santan)	Inner	McQueen Rd	L101	30	14	32	30	14	32	30	16	32	31	15	32	32	22	31	8	11	19	31	16	32
114	Loop 202 (Red Mt)	Inner	Sky Harbor Blvd	L101	29	32	19	29	32	20	31	32	20	32	32	23	31	30	19	24	23	15	32	32	19

The maps in Figures 10 and 11 illustrate the bottleneck delay per person and per heavy truck, respectively, with the top five highlighted in red.

Freeway Bottlenecks

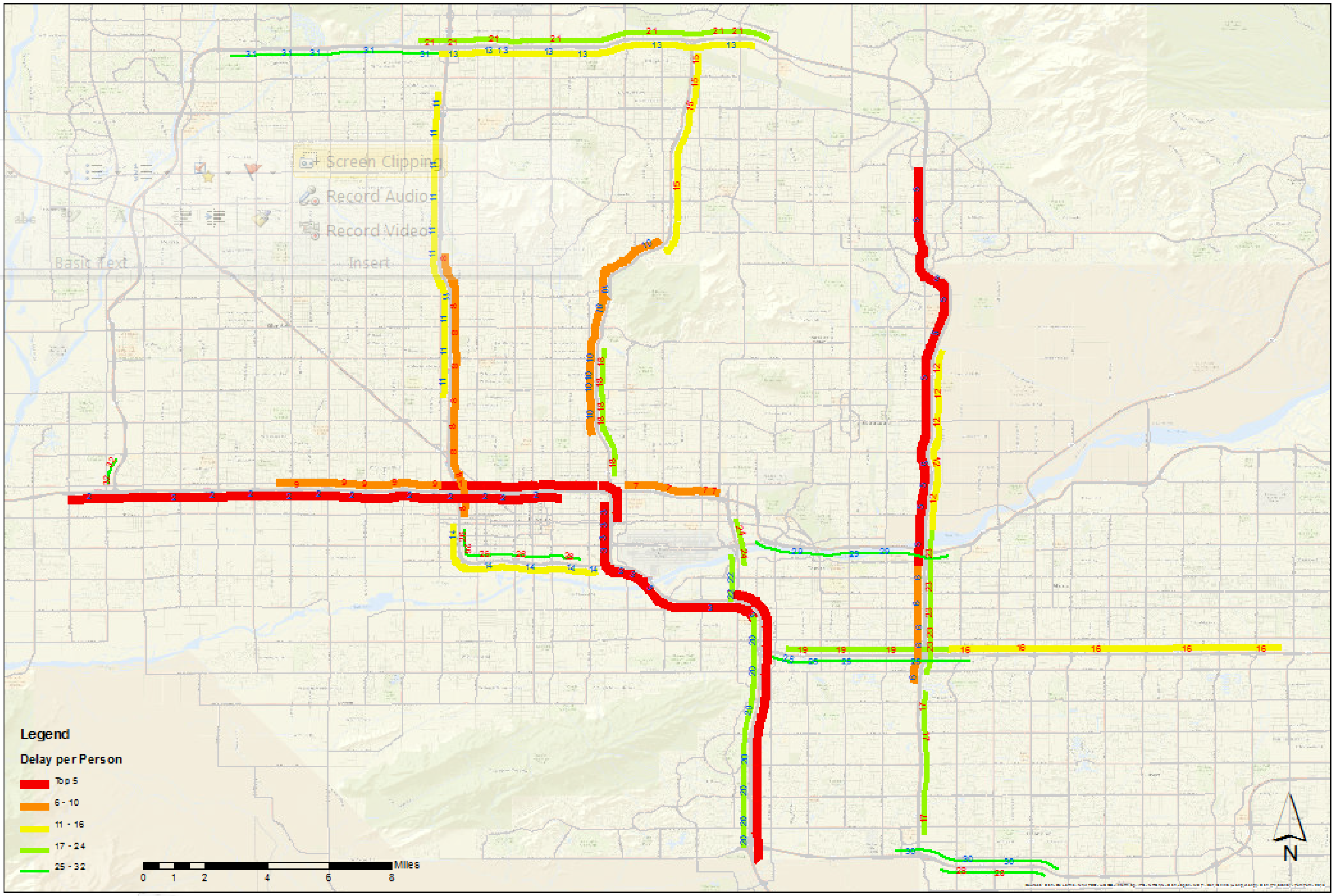

Figure 10: Map of 32 bottlenecks ranked from 1 to 32 for delay per person

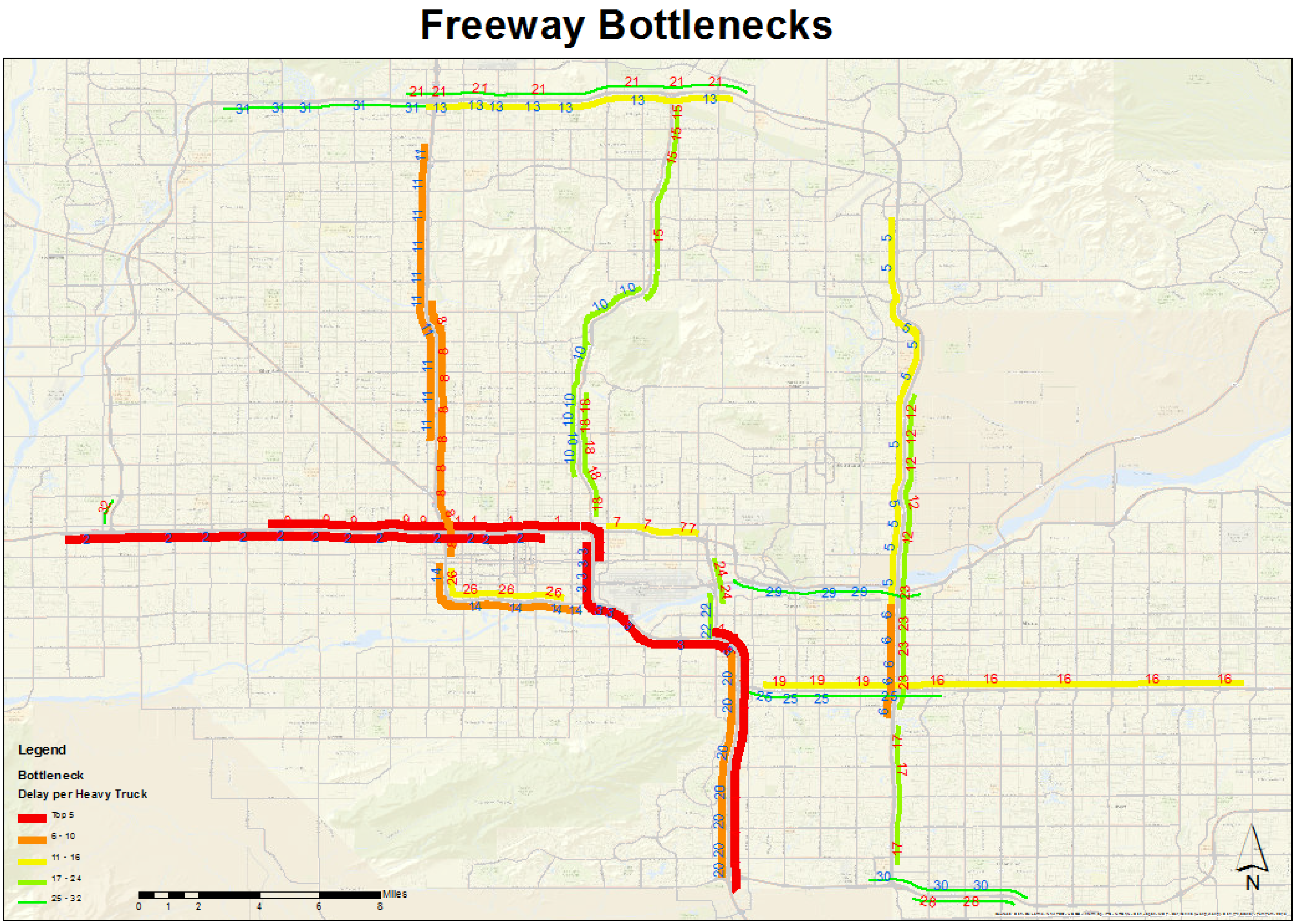

Figure 11: Map of 32 bottlenecks ranked from 1 to 32 for delay per heavy truck

5. Conclusion and Future Work

In conclusion, this report introduced a methodology to conduct bottleneck identification and measurement using an archived private-sector speed database. In the last five to six years, private-sector speed data have become popular for public agencies to use in a variety of studies and applications, and these data have become the new and trending data source for public agencies to look at for mobility analysis. With this methodology established and performed on an annual basis, bottlenecks are now under constant and comprehensive scrutiny given the richness of data, mainly facilitated by innovative mobile communication and crowd-sourcing technologies. In this new "big data" era, public agencies have found a way to study existing bottlenecks quantitatively and figure out solutions through operation and planning processes to effectively remediate bottleneck congestion.

The same bottleneck identification algorithm was applied to the arterial network following the procedure stated in section 3. The algorithm results for the arterial network were not intuitive and as expected. Several factors that contribute to this are:

- This algorithm is designed for using archived average speed data to identify the bottleneck specifically in uninterrupted flow situations. Arterial traffic is interrupted flow, and intersection delay plays a huge role in determining the travel delay on a particular link. This makes the speed profile rather irrelevant between adjacent arterial links.
- The accuracy of speed data on arterial streets is not as good as on freeways, due to a lower sample rate and more complex traffic conditions.

This report highlights the first half of the MAG bottleneck study. During the second half of the study, the following tasks are planned:

- Following the same approach, repeat the work of bottleneck measurement for years 2010, 2011, and 2013. Produce the bottleneck rankings per key measures (e.g., delay per vehicle and delay per heavy truck) for each year, and track the bottleneck's congestion and its performance across the span of four years.
- Categorize congestion by source on these bottlenecks. Investigate the relationship between traveler information data and traffic data to categorize the congestion into seven root causes per the Federal Highway Administration, and continue to quantitatively break down these congestion sources on every bottleneck. These seven root causes are:
    - Traffic incidents,
    - Work zones,
    - Weather,
    - Fluctuation in normal traffic,
    - Special events,
    - Traffic control devices, and
    - Physical bottlenecks (capacity).
- Identify a case study area that contains several severely congested bottlenecks in the region, and collect additional data such as vehicle trajectory, OD, and ramp access data for these

bottlenecks. When examining the distribution of bottlenecks, particularly those high-ranked bottlenecks, it has been found that many are located around two freeway-to-freeway interchanges in the downtown Phoenix area. Specifically, bottlenecks 8, 7, 26, and 37 are among the top five in delay per vehicle and delay per heavy truck. To further understand these bottlenecks, a thorough and comprehensive case study will be conducted, a micro-simulation model will be established, and an in-depth analytical report including bottleneck visualization will be produced.